

# iVIEW

## EDITOR'S PAGE

### RV Form and Function

#### A Piston Pump, Vortex Impeller, or Hydraulic Ram?

Partho P. Sengupta, MD, Jagat Narula, MD, PhD

The iPIX by Saremi et al. (1) in this issue of *JACC* highlights the precision of current imaging techniques in displaying the complex 3-dimensional structure of the right ventricle (RV). The investigators illustrate the intricacy of normal RV geometry, highlighting the distributions of anatomical folds, irregular trabeculations and, more importantly, the RV infundibulum. These remarkable pictures only make one question more on the physiological relevance of the complex RV geometry. The separation of a thin-walled, highly compliant RV and a thick-walled, highly contractile left ventricle (LV) has been justified to the evolutionary needs of air breathing and high metabolism (2). The separation of the right and the left circulations ensure presence of lower blood pressures in the pulmonary circulation; in its absence the thin blood-gas barrier required for high oxygen demands would be breached with the least amount of exertion. Given that the 2 chambers require being separate, there has been little information, however, to justify why the geometry of the 2 chambers need to be so different.

**RV as a piston pump.** Longitudinal shortening and base-to-apex piston-like motion of the atrioventricular plane have been suggested to be a greater contributor to RV stroke volume than short-axis or circumferential shortening. A number of measurements have therefore been explored, including the tricuspid annular plane systolic excursion (TAPSE), RV free wall annular velocities, and longitudinal strain of the RV free wall. However, RV function is sustainable even in the absence of RV free wall activity, which can be completely excised and replaced by an inert prosthetic patch as long as LV function is preserved. These observations question

the longitudinal traction of the tricuspid annulus as the basis for the pyramid-shape of the RV. Moreover, the conventional echocardiographic indexes based on RV longitudinal contraction have been inconsistent and show poor correlation with RV global ejection fraction, at least in a post-operative population with congenital heart diseases.

**RV as a vortex impeller.** We have previously discussed the structure and function of the LV in relation to the sequence of blood flow, which is characterized by the formation of an asymmetric larger anterior directed vortex formation. However, the RV geometry theoretically allows for an easy intraventricular transit of blood which does not require sustained vortex formation (Fig. 1A). Only transient vortex rings develop below the tricuspid orifice, that dissipate quickly. The intraventricular RV flow has been confirmed in vivo using echocardiography contrast particle imaging velocimetry (Figs. 1B and 1C) and has only revealed the formation of vortices transiently in the tricuspid inflow region that vanish rapidly during diastole. The average flow in the RV during systole and diastole therefore appears largely streamlined.

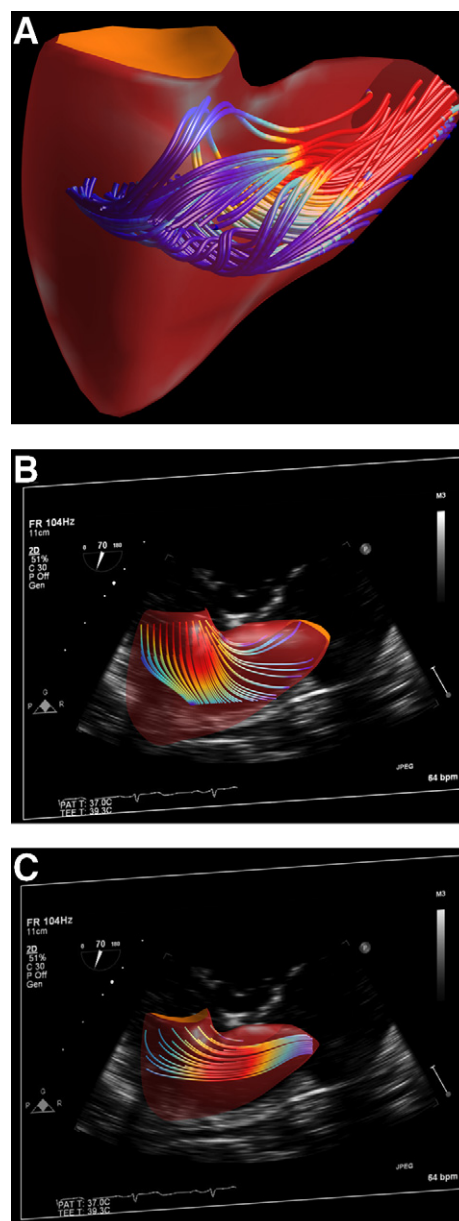
**RV as a hydraulic ram.** A hydraulic ram is an ancient cyclical water pump that was invented in the 17th century which is based on developing a pressure surge when fluid in motion is forced to stop (or change direction) suddenly. The pressure built is then used to lift water to a point higher (supply head) than where the water originally started (deliver head) with the least energy expenditure (Fig. 2). Blood flowing into the ram under low pressure leaves it under much higher pressure. The idea of the cardiac chambers therefore working on a principle similar to that of the water ram was prevalent in the mid-20th century (3).

In a hydraulic ram (Fig. 2) the water in the drive pipe flows under gravity and picks up kinetic energy until the waste valve suddenly closes due to increasing drag. The momentum of the water flow in the supply pipe against the now

closed waste valve causes a pressure surge that opens the delivery valve, and forces water to flow into the delivery pipe. The delivery pipe leads to an air chamber that cushions the pressure development. The air contained in chamber is compressed, and then it expands and forces the water from the chamber into the outflow tube. As the flow reverses, the delivery check valve closes. If all water flow has stopped, the loaded waste valve reopens, which allows the process to begin again. The direct analogy of the hydraulic ram with the function of the LV is not feasible because of the presence of a dominant vortex-aided design of the LV. However, the potential of RV function modeled on a hydraulic ram seems attractive. The most compelling aspect of the analogy is the development of a pulsatile flow from a continuous flow and the striking similarity between the pressure curve tracings obtained from the water ram and the ventricle.

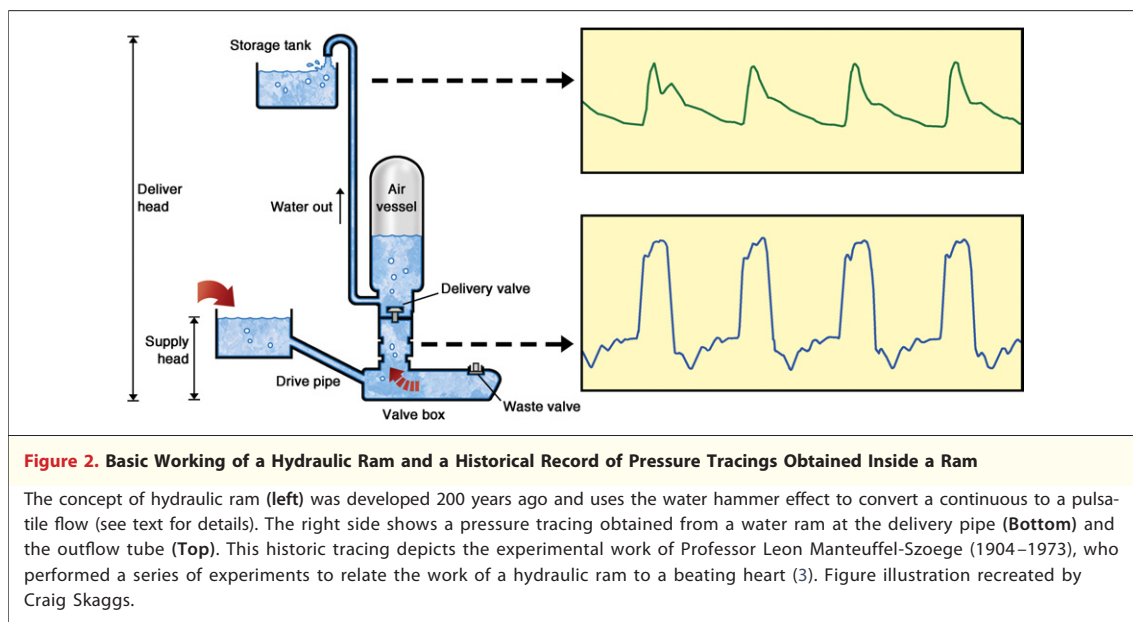
**Role of LV in RV function.** The left side of the heart plays a major role in assisting RV ejection. The septum thickens equally in both the RV and LV directions besides shortening along its apex-to-base longitudinal axis and contributes >60% of the systolic contractile force of the RV (4); injecting glutaraldehyde into the septum similarly reduces RV pressure development. In addition, the end-diastolic position of the septum may present as a form of septal preload and influence septal motion during systole. Echocardiographic analyses confirm interventricular septum (IVS) shift with an increase in RV preload and influence the maximal IVS deformation and RV function. Thus, ventricular interdependence creates a balance of forces at the interventricular sulcus. The forces in the LV free wall are balanced across forces in the RV free wall and the interventricular septum. Thus changing 1 wall can directly affect all 3 walls.

**The role of right atrium.** The blood streams from the superior and inferior vena cava produce a noncolliding flow rotation and vortex in the right atrium (RA). Due to the characteristic morphology of the RA and its role as a receiving and dilating chamber during ventricular systole, flow keeps continuously arriving into the RA even when the tricuspid valve is closed. One could imagine that without this role of the RA cavity, the shutting of the tricuspid valve would halt the whole column of venous blood, and a great pressure wave would be generated from this stopping of blood flow. These large changes in pressures waves in the absence of unyielding veins



**Figure 1. 3- and 2-Dimensional Flow Across the RV and RV Outflow Tract**

(A) The 3-dimensional (3D) helical flow is shown during systole; streamlines are color-coded (blue to red) with the local blood kinetic energy. Right ventricle (RV) intracavity flow is computed by using numerical simulation of the equations governing blood motion inside an RV geometry obtained by 3D echocardiography. The image was recreated for *JACC* by Gianni Pedrizzetti and Jan Mangual. (B and C) Transesophageal contrast particle imaging velocimetry has been performed in a patient with normal RV function. Average flow in systole (B) and diastole (C) are shown with streamlines that are color coded (blue to red) with the local blood kinetic energy. In contrast to the left ventricle where the intracavity flow is dominated by vortex formation, dominant vortical flow structures are not seen in the average flow profile of the RV. Transient vortices are formed in the inflow region, which rapidly dissipate in diastole. Since the flow obtained in this example is in a 2-dimensional plane, it may underestimate the helical spin seen in the RV infundibulum.



could be large enough to damage the venous system. This safety action of dilating atria as a receiving chamber remains undervalued.

**The role of RV inflow and body.** When the hydraulic ram model is invoked for the RV function, the septum may be perceived as the air cushion, transducing forces developed across the septum in the LV cavity for systolic RV ejection. Indeed, the strong correlation between LV pressure and RV performance, the impairment of RV function in isovolumic rabbit hearts with reduced LV free-wall contractility, and the detrimental effects of surgical transection of the LV free wall on RV developed pressure, which returns to normal after repair of the LV wall, suggests that the RV derives substantial support during ejection from the LV work.

The timing and the direction of blood flow in the LV and RV also deserve consideration. The tricuspid valve opens before the mitral valve, giving the RV an advantage in directing and loading the blood flow over the unloaded septum. Conversely, the RV ejection exceeds the LV ejection, which could allow the fluid forces developed across the LV side of septum to maximally influence the RV ejection. The tilt in the direction of the tricuspid valve plane and the streaming of flow from the RA allows maximum impact of the preload over the convex surface of the septum (Fig. 1B), while the trabeculae would provide increased surface area for preload distribution. The septum would be shifted and deformed (right to left shift) with greater right heart preload. The

thin RV free wall would accommodate increasing blood volume that primarily loads the septum, the motor and force-generating surface of the RV.

It is also quite intriguing to note that the larger anterior vortex developed in the LV cavity primarily flogs the septum and anteroseptal region of the LV wall before being redirected into the LV outflow. This congruence in design, such that fluid forces in the LV cavity are directed over the septum, influences interventricular interactions. Indeed, experimental studies have shown that rapid removal and addition of fluid into the LV causes immediate changes in RV pressure and volume outflow (5).

**The role of RV outflow.** And finally, it is tempting to hypothesize what potentially could be the reason for the RV to have a long outflow. Firstly, a long outflow could allow a larger surface area for maximal interaction between the LV and RV. Secondly, the entry of blood under pressure from the RV body into narrowed RV outflow would allow development of flow acceleration for development of a propulsive jet. Thirdly, the flow across the RV outflow may allow development of a helical spin in the flow. The numerical model (Fig. 1A) and 4-dimensional flow using magnetic resonance imaging have shown presence of helical flow in the RV outflow and pulmonary arteries. Presence of helical spin, just like a gun barrel, provides better directional stability and minimizes flow separation and turbulence.

In all, some of the historical models of cardiac function discussed here may need to be revisited.

Furthermore, collective evidence from imaging techniques and quantitative and numerical methods will eventually help piece together the functional significance of the intriguing RV chamber.

---

## REFERENCES

1. Saremi F, Ho SY, Sanchez-Quintana D. Morphological assessment of the RVOT: CT and CMR imaging. *J Am Coll Cardiol Img* 2013;6:631–5.
2. Jensen B, Nielsen JM, Axelsson M, Pedersen M, Löfman C, Wang T. How the python heart separates pulmonary and systemic blood pressures and blood flows. *J Exp Biol* 2010;213:1611–7.
3. Manteuffel-Szoege L. Energy sources of blood circulation and the mechanical action of the heart. *Thorax* 1960;15:47–53.
4. Damiano RJ, LaFollette P, Cox JL, Lowe JE, Santamore WP. Significant left ventricular contribution to right ventricular systolic function. *Am J Physiol* 1991;261:H1514–24.
5. Chow E, Farrar DJ. Right heart function during prosthetic left ventricular assistance in a porcine model of congestive heart failure. *J Thorac Cardiovasc Surg* 1992;104:569–78.